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RESEARCH MEMORANDUM

DEVELOPMENT OF A SUPERSONIC AREA RULE AND AN APPLICATION TO THE DESIGN OF A WING-BODY COMBINATION HAVING HIGH LIFT-TO-DRAG RATIOS

By Richard T. Whitcomb and Thomas L. Fischetti

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

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SUMMARY

As an extension of the transonic area rule, a concept for interrelating the wave drags of wing-body combinations at moderate supersonic speeds with axial distributions of cross-sectional area has been developed. The wave drag of a combination at a given supersonic speed is related to a number of distributions of cross-sectional areas as intersected by Mach planes. On the basis of this concept and other design procedures, a structurally feasible, swept-wing—indented-body combination has been designed to have significantly improved maximum lift-to-drag ratios over a range of transonic and moderate supersonic Mach numbers. The wing of the combination has been designed to have reduced drag associated with lift and, when used with an indented body, to have very low form wave drag. Limited, preliminary experimental results have been obtained for this configuration at Mach numbers up to 1.15. A maximum lift-to-drag ratio of approximately 14 was measured at a Mach number of 1.15.

INTRODUCTION

It was shown in reference 1 that near the speed of sound, the zero-lift drag rise for a thin low-aspect-ratio wing-body combination is primarily dependent on the axial distribution of cross-section area normal to the airstream. Also, it was found that contouring the bodies of wing-body combinations to obtain improved axial distributions of cross-sectional area for the combinations results in substantial reductions in the drag-rise increments at transonic speeds.

More recently, by considering the physical nature of the flow at moderate supersonic speeds, a concept has been developed which should interrelate qualitatively the zero-lift wave drag of wing-body combinations at these speeds with axial distributions of cross-sectional areas.

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On the basis of this concept and other design procedures, a structurally feasible swept-wing—indented-body combination has been designed to have significantly improved lift-to-drag ratios over a range of transonic and moderate supersonic Mach numbers.

Although, at the present time, experimental results have been obtained for this wing-body configuration for only the lower portion of design speed range (Mach numbers up to 1.15), the favorable nature of these limited results has justified the publication of this information, together with the development of the supersonic area rule and the considerations involved in the design, before experimental results for the complete design speed range have been obtained.

CONCEPT FOR INTERRELATING WAVE DRAG WITH AREA DISTRIBUTIONS AT SUPERSONIC SPEEDS

Basis of Concept

The major part of the supersonic wave drag for a wing-body combination results from losses associated with shocks at considerable distances from the configuration. Thus, the wave drag may be estimated by considering the stream disturbances produced by a configuration at these distances. At moderate supersonic speeds, these disturbances may be considered in individual stream tubes, such as A in figure 1. If small induced velocities are assumed, the effects of changes in the configuration arrive at points on this tube along Mach lines which lie on cone segments, such as B. For reasonable distances from the configuration, roughly 2 spans or greater, and normal, relatively low-aspect-ratio wings, the surface of these cone segments in the region of the configuration may be assumed to be the Mach planes, such as C, tangent to the cone segments between the tube A and the axis of symmetry.

Consideration of the propagation of the local effects of the configuration indicates that the variations in the disturbances at the stream tube A generally may be assumed to be approximately proportional to streamwise changes in the normal components of the total areas of the cross sections, such as DD, intersected by these Mach planes. It follows that the wave losses in the stream tube are functions of the axial distribution of these cross-sectional areas. Obviously, the losses in the set of stream tubes along a given radial sector are functions of one axial distribution of cross-sectional area while those in tubes in circumferentially displaced sectors are functions of various distributions determined by sets of Mach planes with axes of tilt rotated about the axis of symmetry. Except for the substitution of streamwise changes of cross-sectional area for singularities, these considerations are essentially the same as those presented by Hayes on page 93 of reference 2.

Procedure for Determining Area Distributions

It follows from the foregoing considerations that the zero-lift wave drag for a wing-body combination at a given moderate supersonic Mach number is related to a number of distributions of the normal components of cross-sectional areas as intersected by Mach planes which are inclined to the stream at the Mach angle m (fig. 2). The various distributions are obtained with the axis of tilt of these Mach planes rolled to various positions around the center line of the configuration. This procedure is illustrated in figure 2. For clarity, the position of the axis of tilt of the Mach plane is maintained and the configuration is rolled. For configurations symmetrical about horizontal and vertical planes, the area distributions are determined for various roll angles θ from 0° to 90°. The approximate wave drag for the combination is an average of functions of a number of area distributions so determined.

The area distributions obtained for the configuration shown in figure 2 with the two representative roll angles are presented at the bottom of the figure. As indicated by these curves, the various distributions for a given Mach number may differ considerably. The partial end-plate effect of the body on the field of the wing affects the applicability of this simplified concept. For most practical combinations, this effect should be of secondary importance. Obviously this relationship reduces to the transonic area rule at a Mach number of 1.0.

This relationship is basically the same as those arrived at recently by R. T. Jones of the NACA, Ames Laboratory, (unpublished) and G. C. Grogan, Jr., of Consolidated Vultee Aircraft Corporation (unpublished) on the basis of the considerations of Hayes.

Application to the Reduction of Wave Drag

On the basis of this concept, the approximately minimum wave drag for a wing-body combination at a given supersonic speed would be obtained by shaping the body so that the various area distributions for this speed are the same as those for bodies of revolution with low wave drag. For most configurations somewhat more satisfactory distributions can be obtained by shaping the body noncircularly rather than axially symmetrically. Obviously, the body contours used should not be such as to cause severe local velocity gradients or boundary-layer separation. In general, for combinations of practical wings with bodies with sufficiently conservative contours, the area distributions for the various values of θ will deviate from the most desirable shapes. The possibilities of improving the various area distributions at and off the design conditions through the use of body indentation are strongly dependent on the geometry of the wing.

DESIGN OF WING-BODY COMBINATION

The wing of the combination has been designed to have reduced drag associated with lift and, when used with an indented body, to have very low form wave drag, on the basis of the concept described in the preceding section, for a range of transonic and moderate supersonic Mach numbers. In particular, the parameters of the wing generally have been selected so that it is possible to obtain with a given body indentation relatively smooth area distributions for the various values of θ (fig. 2) at the Mach numbers under consideration.

Description of Configuration

The configuration is shown in figure 3. The wing has 60° of sweep, an aspect ratio of 4, and a taper ratio of 0.333 and is cambered and twisted. It has NACA 64-series airfoil sections which vary in thickness ratio from 12 percent at the root to 6 percent at 50 percent semispan and then remains constant at 6 percent to the tip as shown in figure 4. The ordinates of the wing sections are listed in table I.

The body shape used as a basis for the design of the indented configuration discussed herein is that for the body described in reference 3. The body has been indented axially symmetrically to obtain relatively smooth area distributions at a Mach number of 1.4 (fig. 5). The ordinates for the body are listed in table II. The ratio of the body volume to the two-thirds power to the wing area for this combination is the same as that for the configuration of reference 3. The body incidence is 5° with respect to the reference plane of the wing (fig. 4).

Considerations Involved in Design

Wing sweep.- A comparison of the area distributions for moderate supersonic speeds for various wing plan forms in combination with indented bodies has indicated that the use of body indentation results in the greatest relative improvements in the area distributions for the various values of θ (fig. 2) at and off the given design Mach numbers when the wing leading and trailing edges are swept behind the Mach lines. Also, the experimental results obtained thus far have indicated that the actual effects of indentation on drag approach the estimated effects most closely for such conditions (ref. 1, for example). With the higher wing aspect ratios which become structurally feasible because of the thicker wing sections allowed through the use of body indentation, swept wings with the leading and trailing edges swept behind the Mach lines have the lowest drags associated with lift (ref. 4). With the 60° of sweep chosen for the configuration described herein, these advantages should be realized over a wide range of moderate supersonic speeds.

Wing section thickness ratios.- Analysis of area distributions and experimental results (ref. 5) have indicated that, generally, the effectiveness of a body indentation in reducing wave drag at and off design Mach numbers and at lifting conditions is considerably greater for a wing with section thickness ratios that decrease from root to tip than for one with a uniform thickness ratio equal to the mean value for the tapered-thickness wing. The estimated variation of supersonic wave drag with change in wing thickness ratio at a given Mach number for wings with bodies indented to obtain the smoothest area distributions for each combination is generally less pronounced than that for the same wings in combination with an unindented body. It follows that the most satisfactory compromise inboard section thickness ratios should be considerably higher for indented configurations than for normal combinations. However, because of the limitations to the magnitude of feasible indentations, as discussed previously, body indentation obviously cannot be used to reduce the drag increments of indefinite increases in wing thickness ratios.

Wing aspect ratio and structural characteristics.- With the wing swept behind the Mach line, the drag due to lift is reduced by increasing the aspect ratio (refs. 4 and 5). Because of the relatively thick wing sections allowed with body indentation, compromise aspect ratios significantly higher than those previously used for practical configurations can now be considered. An actual wing of the relatively high aspect ratio configuration proposed herein appears to be structurally feasible. With the usual type of wing construction, the deflection of the wing of this configuration under a given load at the 70-percent-semispan station would be roughly the same as that for bomber configurations considered feasible by designers and approximately half that for the highly swept wing discussed in reference 3.

Body contours and area distributions.- With the body indentation used, the axial distribution of cross-sectional area for the combination for the median value of θ (45°) at the design Mach number of 1.4 (fig. 5) is approximately the same as that for the body used as a basis for the design. At the extreme values of θ (0° and 90°) the distributions differ somewhat from those for the basic body; however, the estimated drag increment for the combination associated with such variations in the area distributions is negligible. The area distributions for Mach numbers between 1.0 and 1.6 are all relatively smooth. Those obtained at $m = 1.0$ are shown in figure 5. At Mach numbers greater than 1.6, the distributions become relatively irregular.

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The area distributions obtained for this combination at Mach numbers up to 1.6 are considerably smoother than those obtained for the same conditions for unswept, moderately swept, and delta wings with approximately the same aspect ratio and mean section thickness ratios in combination with indented bodies. As examples of such distributions, those obtained for a 45° swept wing with an aspect ratio of 4, a taper ratio of 0.3, and NACA 65A006 airfoil sections in combination with a body indented axially symmetrically to improve the area distributions for a Mach number of 1.4 are presented in figure 6.

Wing twist and camber.- Recent unpublished results obtained at low supersonic speeds indicate that the favorable effects of twist and camber on the lift-to-drag ratios can be added to those of body indentation. The basis for the twist and camber used is the mean surface form theoretically required for a uniform load at a lift coefficient of 0.25 at a Mach number of 1.4 (ref. 4). This theoretical form has been modified by reducing the camber and twist near the wing-body juncture (see fig. 4). An analysis of the effects of the body on the induced field due to lift at supersonic speeds has indicated that such a modification should improve the drag associated with the lift produced by camber and twist.

PRELIMINARY EXPERIMENTS

Apparatus and Methods

Preliminary results for the configuration described in the preceding section were obtained in the Langley 8-foot transonic tunnel. The wing was tested not only in combination with the body designed to obtain smooth area distributions at a Mach number of 1.4, but also with the basic body and a body indented so that the axial distribution of cross-sectional area for the combination for a Mach number of 1.0 is the same as that for the basic body alone. The axial distributions of cross-sectional area for a Mach number of 1.0 for these additional combinations are presented in figure 7. The model dimensions are shown in figure 3. All data presented are essentially free of the effects of wall-reflected disturbances. The maximum errors of the drag coefficients at transonic speeds are of the order of ±0.0005; those of the lift coefficients, ±0.002. These limits include the effect of possible errors in the measurements of angle of attack. The results have been adjusted to the condition of stream static pressure on the base of the body.

Results and Discussion

Lift and drag coefficients.- The variations of the angle of attack and drag coefficient with lift coefficient for the various test Mach numbers are presented in figure 8. The coefficients are based on a wing area of one square foot.

Lift-to-drag ratios.- The maximum lift-to-drag ratio for the combination with the body indented for a Mach number of 1.4 at the maximum test Mach number of 1.15 is 14.3 (fig. 9). This value was obtained at a lift coefficient of 0.27. The value is only 10 percent less than that obtained for the same combination at subsonic Mach numbers. The subsonic maximum lift-to-drag level for this configuration is approximately the same as the highest values previously obtained at these speeds for structurally comparable wing-body combinations intended for supersonic flight.

Near a Mach number of 1.0, the lift-to-drag ratics obtained for the combination with the body indented for a Mach number of 1.4 are considerably less than those obtained for the combination with the body indented for a Mach number of 1.0 as indicated by the solid line in figure 9. An analysis of the area distributions for this Mach number presented in figure 5 indicates that only a small portion of this difference can be attributed to the additional wave drag associated with the less smooth area distribution for the Mach number 1.4 combination. The fact that a similar difference was also obtained at subsonic Mach numbers suggests that it is due primarily to effects of the variation of the body on the boundary layer on the combination.

At a Mach number of 1.15, the lift-to-drag ratios for the configuration indented for a Mach number of 1.4 are approximately 50 percent greater than those for the basic-body combination. (The relative improvement would have been slightly less if the size of the basic body had been decreased to have the same volume as that of the indented body.) The values obtained for the basic-body configuration are somewhat greater than those measured for other structurally feasible unindented combinations with moderately swept, unswept, and delta wings (ref. 6, for example). A comparison of the drag coefficients obtained for two combinations for a lift coefficient of 0.05 (fig. 10) indicates that this improvement in lift-to-drag ratio is due primarily to a significant reduction of the minimum pressure drag. However, a comparison of the drag variations with Mach number for various lift coefficients for the indented combination indicates that this improvement is also due in part to an elimination of the additional pressure-drag rise with Mach number at lifting conditions.

The addition of a complete afterbody, tail surfaces, engine housing, canopy, and so forth obviously will reduce the maximum lift-to-drag ratios for a complete configuration to values somewhat below those measured for the wing-body combination. Such reduction at supersonic speeds should be minimized by adding the components in such a manner that the area distributions for the combination remain smooth.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 18, 1953.

Richard T. Whitcomb
Richard T. Whitcomb
Aeronautical Research Scientist

Thomas L. Fischetti
Thomas L. Fischetti
Aeronautical Research Scientist

Approved: Eugene C. Draley
Eugene C. Draley
Chief of Full Scale Research Division

lc

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TABLE I

AIRFOIL ORDINATES

Chord station	Ordinate, percent chord					
	10-percent-semispan station (c = 8.40 in.)		20-percent-semispan station (c = 7.80 in.)		40-percent-semispan station (c = 6.60 in.)	
	Upper surface	Lower surface	Upper surface	Lower surface	Upper surface	Lower surface
0	0.06	0.06	0.12	0.12	0.29	0.29
.5	1.09	-.70	1.00	-.67	.92	-.30
.75	1.29	-.84	1.18	-.82	1.05	-.36
1.25	1.66	-1.09	1.44	-1.05	1.26	-.58
2.5	2.07	-1.74	1.93	-1.50	1.67	-.91
5	2.52	-2.56	2.59	-2.12	2.23	-1.33
10	3.09	-3.93	3.36	-3.16	2.96	-1.91
15	3.35	-5.22	3.77	-3.98	3.46	-2.32
20	3.45	-6.20	4.67	-4.00	3.79	-1.70
30	3.14	-7.71	4.04	-5.80	3.97	-3.35
40	2.41	-8.82	3.53	-6.64	3.82	-1.79
50	1.05	-9.42	2.49	-7.04	3.27	-3.89
60	-.74	-9.64	1.05	-7.16	2.38	-3.85
70	-2.68	-9.61	-.64	-7.00	1.11	-3.70
80	-4.77	-9.40	-2.53	-6.82	-.30	-3.58
90	-6.88	-9.18	-4.50	-6.68	-1.80	-3.44
100	-8.82	-8.94	-6.48	-6.50	-3.26	-3.28

Chord station	Ordinate, percent chord					
	60-percent-semispan station (c = 5.40 in.)		80-percent-semispan station (c = 4.20 in.)		100-percent-semispan station (c = 3.00 in.)	
	Upper surface	Lower surface	Upper surface	Lower surface	Upper surface	Lower surface
0	0.65	0.65	0.95	0.95	1.97	1.97
.5	1.11	.24	1.55	.59	2.50	1.50
.75	1.28	.17	1.67	.50	2.57	1.43
1.25	1.45	0	1.86	.36	2.83	1.33
2.5	1.78	-.26	2.21	.14	3.20	1.17
5	2.20	-.61	2.76	-.07	3.77	.93
10	2.85	-1.04	3.52	-.31	4.56	.63
15	3.33	-1.28	4.19	-.43	5.10	.53
20	3.72	-1.46	4.62	-.48	5.60	.50
30	4.07	-1.72	5.22	-.57	6.34	.47
40	4.02	-1.91	5.36	-.62	6.53	.53
50	3.78	-1.87	5.12	-.55	6.40	.77
60	3.24	-1.74	4.62	-.19	6.00	1.13
70	2.39	-1.43	3.88	.09	5.36	1.50
80	1.35	-1.15	2.91	.36	4.53	2.00
90	.21	-1.11	1.93	.59	3.70	2.40
100	-.09	-1.00	.88	.83	2.83	2.83

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TABLE II

BODY COORDINATES

(a) Forebody

Fuselage station	Radius, in.
0	0
.5	.165
1.0	.282
1.5	.378
2.0	.460
2.5	.540
3.0	.612
3.5	.680
4.0	.743
4.5	.806
5.0	.862
5.5	.917
6.0	.969
6.5	1.015
7.0	1.062
7.5	1.106
8.0	1.150
8.5	1.187
9.0	1.222
9.5	1.257
10.0	1.290
10.5	1.320
11.0	1.350
11.5	1.380
12.0	1.405
12.5	1.430
13.0	1.452
13.5	1.475

(b) Afterbody

Fuselage station	Radius, in.		
	Basic body	Body indented for M = 1.4	Body indented for M = 1.0
14.0	1.493	1.461	1.470
14.5	1.512	1.440	1.460
15.0	1.526	1.410	1.440
15.5	1.540	1.365	1.400
16.0	1.552	1.318	1.360
16.5	1.565	1.270	1.320
17.0	1.575	1.226	1.260
17.5	1.585	1.195	1.220
18.0	1.590	1.110	1.190
18.5	1.598	1.150	1.170
19.0	1.602	1.140	1.150
19.5	1.606	1.140	1.140
20.0	1.606	1.160	1.140
20.5	1.604	1.200	1.160
21.0	1.602	1.250	1.200
21.5	1.600	1.280	1.250
22.5	1.587	1.310	1.299
23.5	1.570	1.335	1.328
24.0	1.560	1.345	1.340
25.0	1.532	1.350	1.350
26.0	1.501	1.350	1.350
27.0	1.460	1.330	1.330
28.0	1.414	1.310	1.310
29.0	1.364	1.271	1.280
30.0	1.305	1.230	1.230
31.0	1.231	1.180	1.180
31.7	1.185	1.150	1.150

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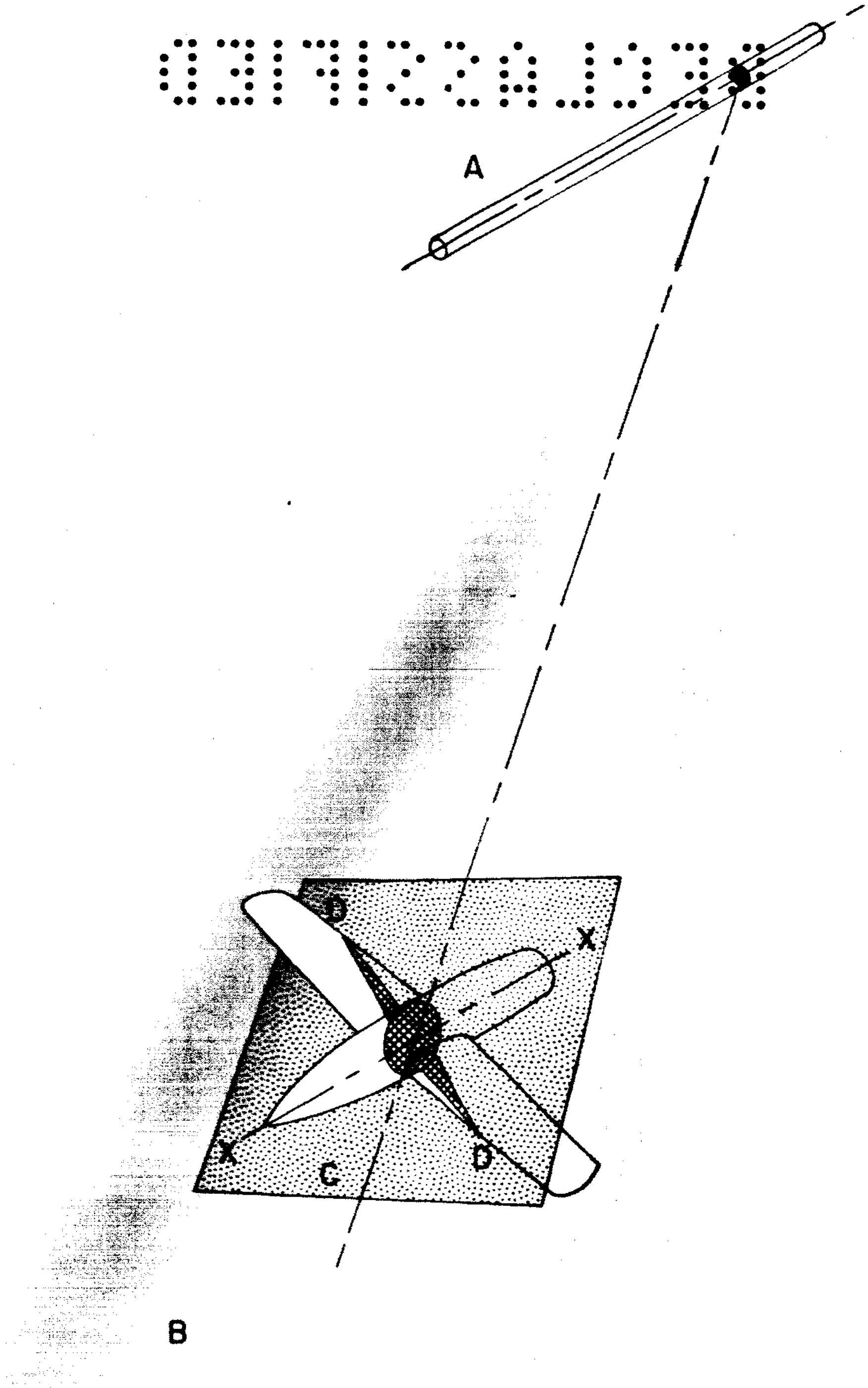

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Figure 1.- Geometric relations considered in developing area rule for supersonic speeds.

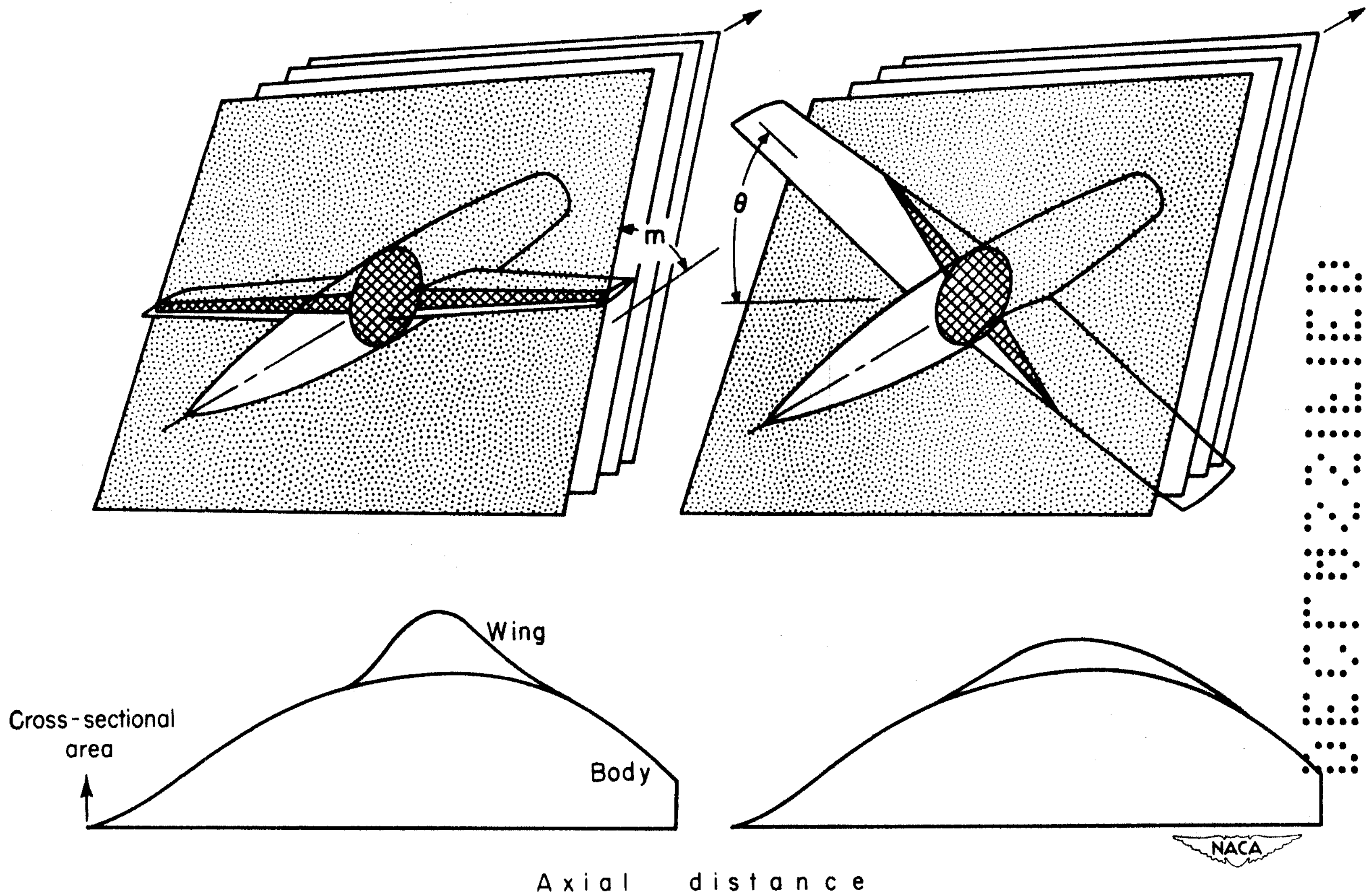

Figure 2.- Procedure for determining area distributions related to wave drag at moderate supersonic Mach numbers.

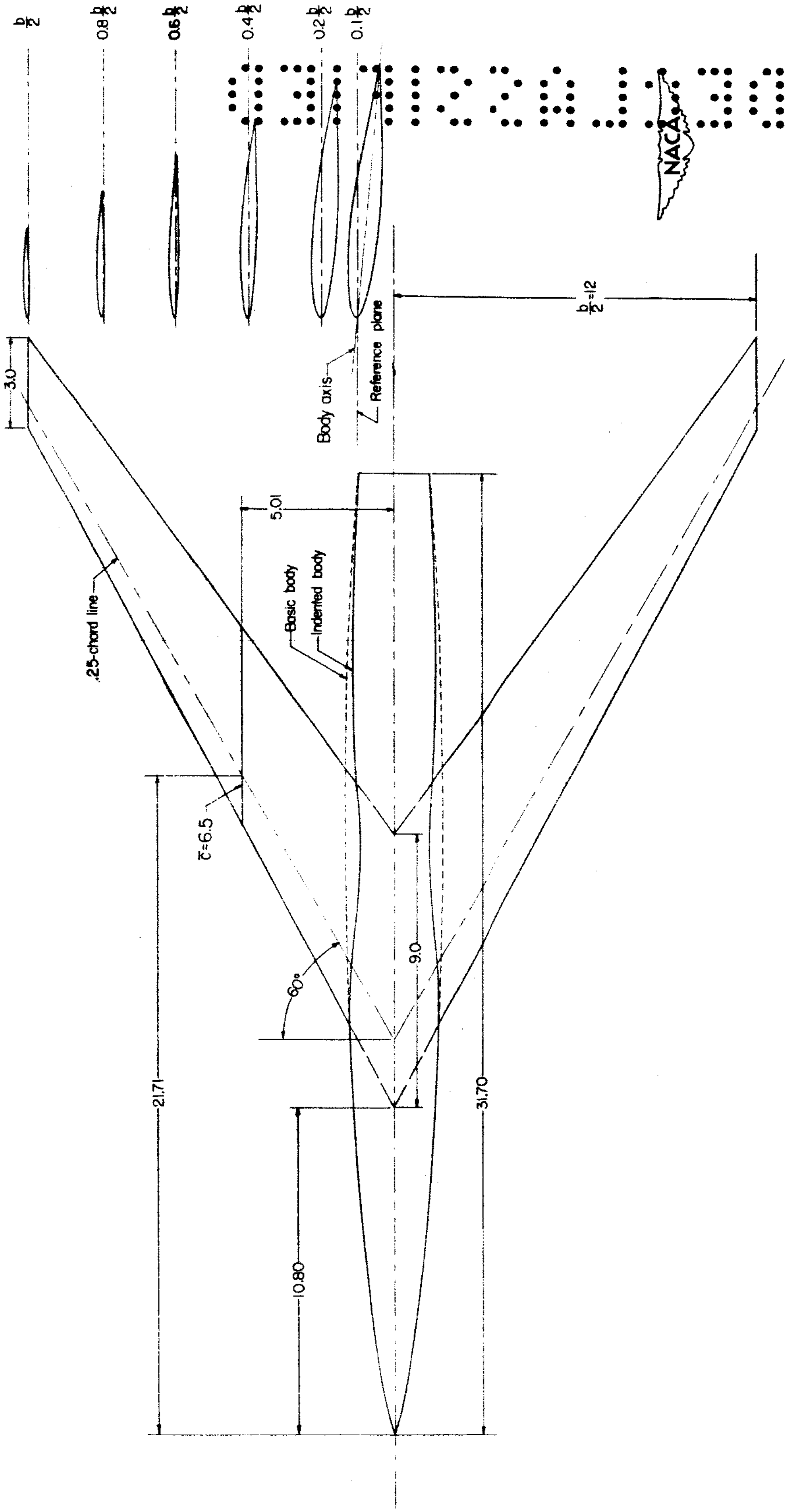

Figure 3.- Dimensions of model of wing-body configuration. All dimensions are in inches.

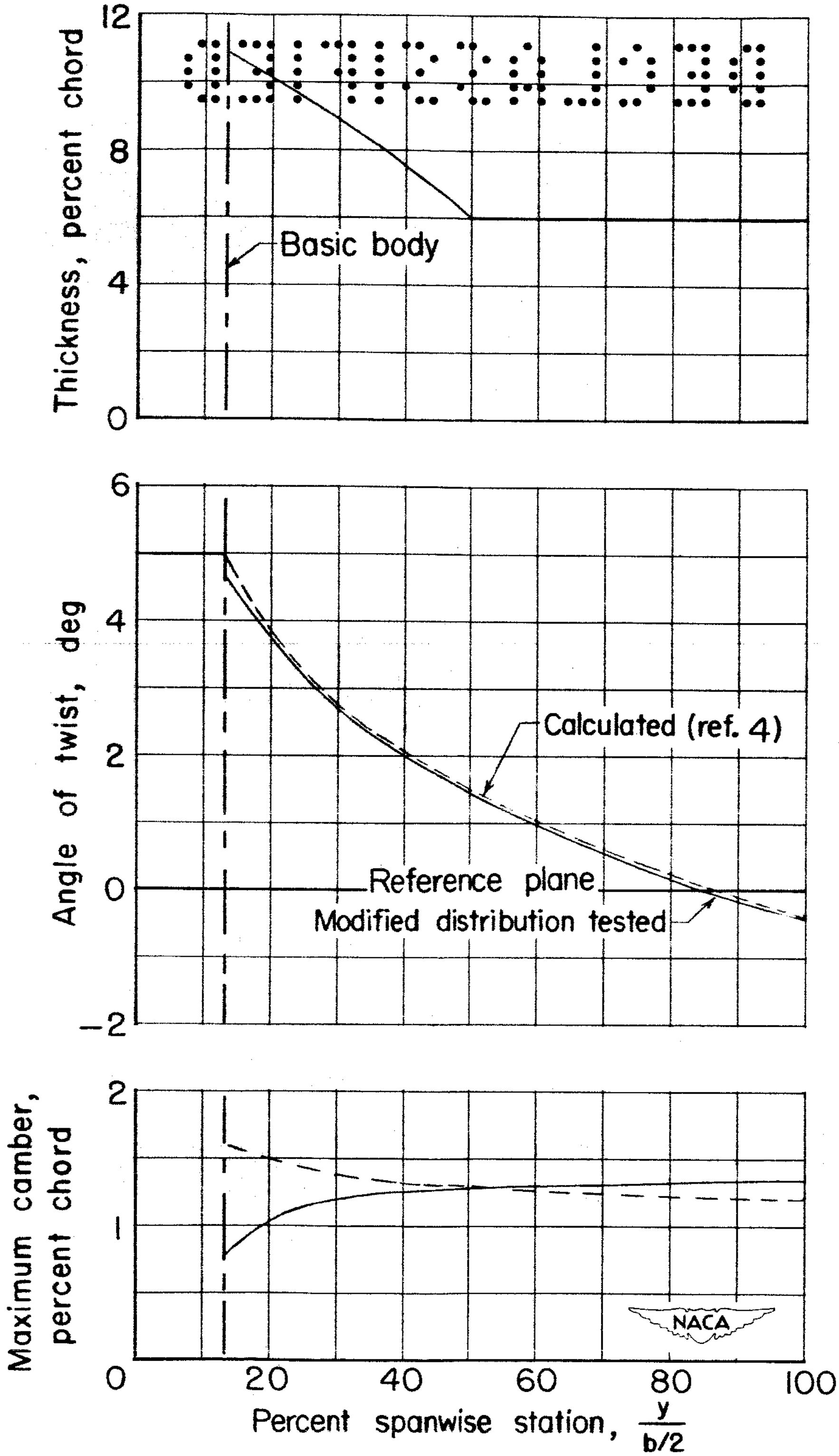

Figure 4.- Spanwise distributions of section thickness ratio, angle of twist, and maximum camber for wing-body configuration.

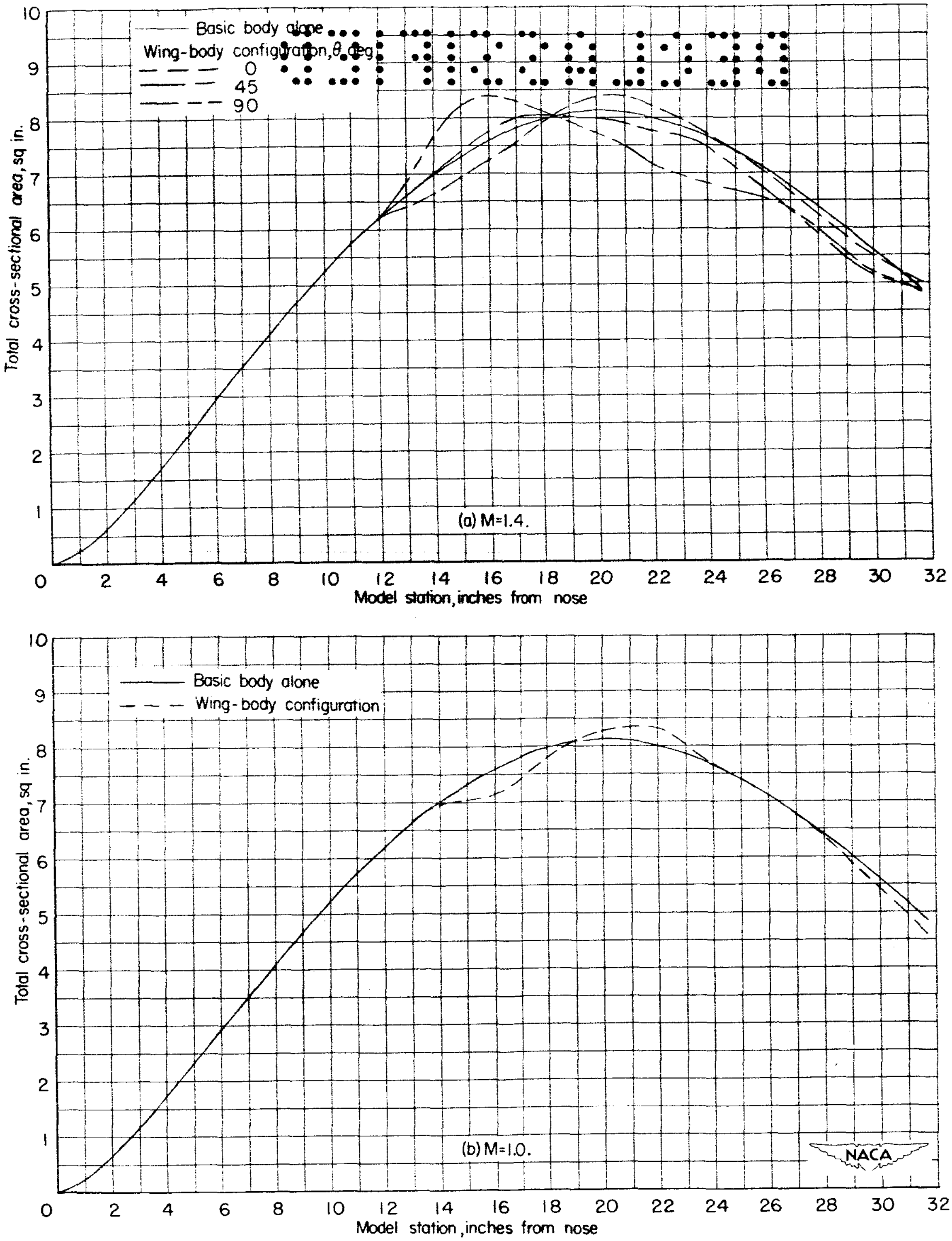

Figure 5.- Representative axial distributions of cross-sectional area for wing in combination with body indented for M = 1.4 at M = 1.4 and 1.0.

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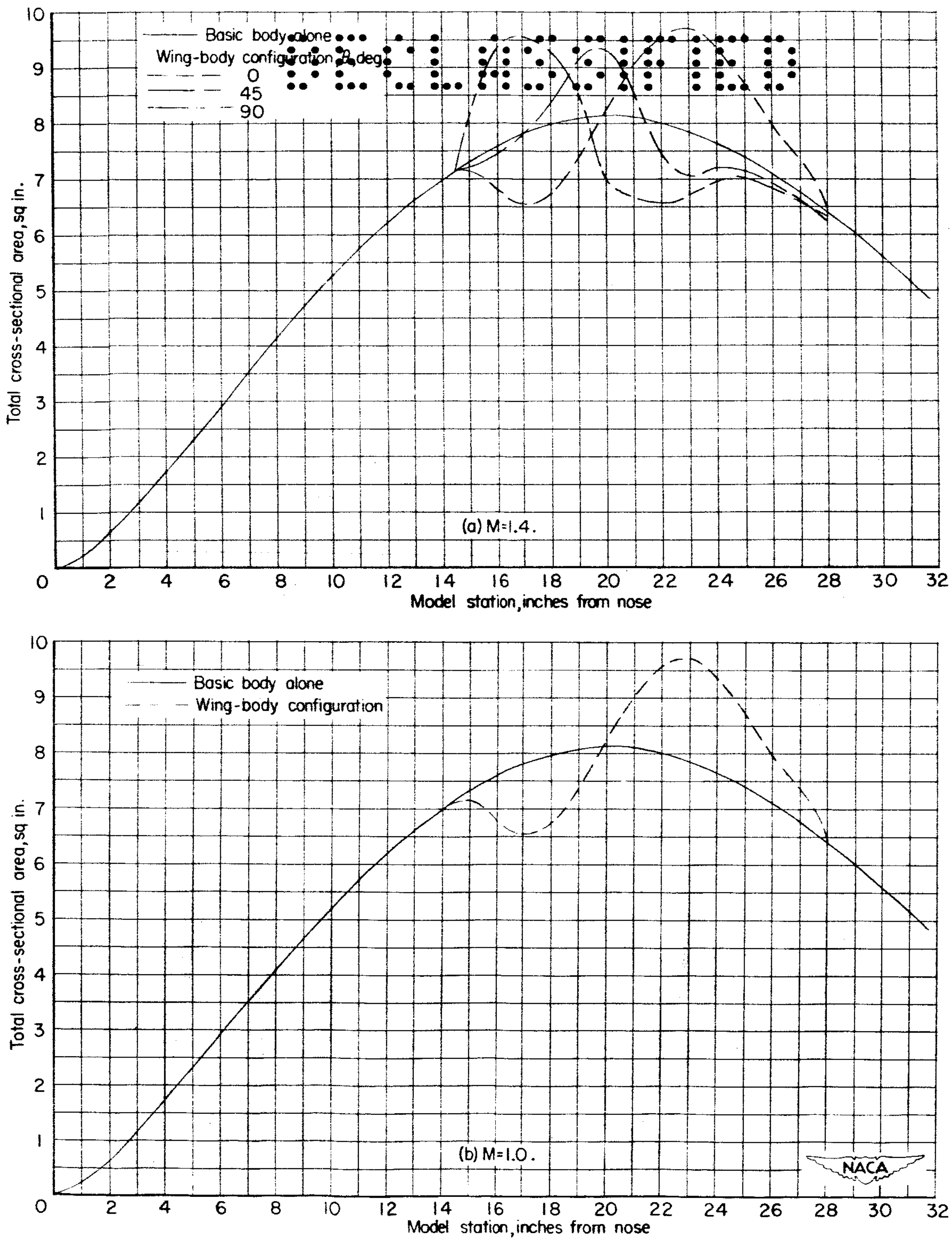

Figure 6.- Representative axial distributions of cross-sectional area for a 45° swept wing in combination with a body indented for $M = 1.4$ at $M = 1.4$ and 1.0.

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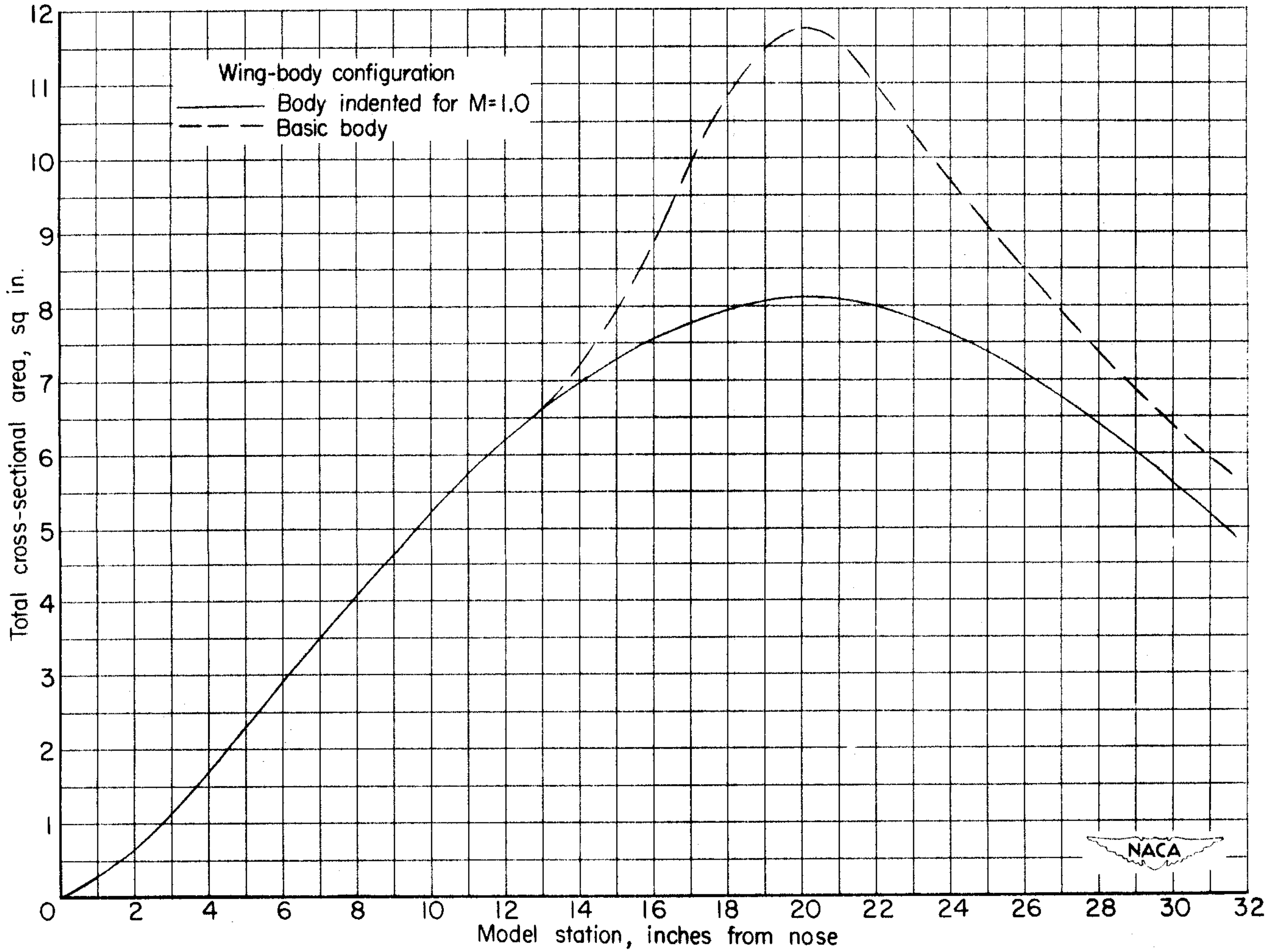

Figure 7.- Axial distribution of cross-sectional area for wing in combination with the basic body and a body indented for M = 1.0 at M = 1.0.

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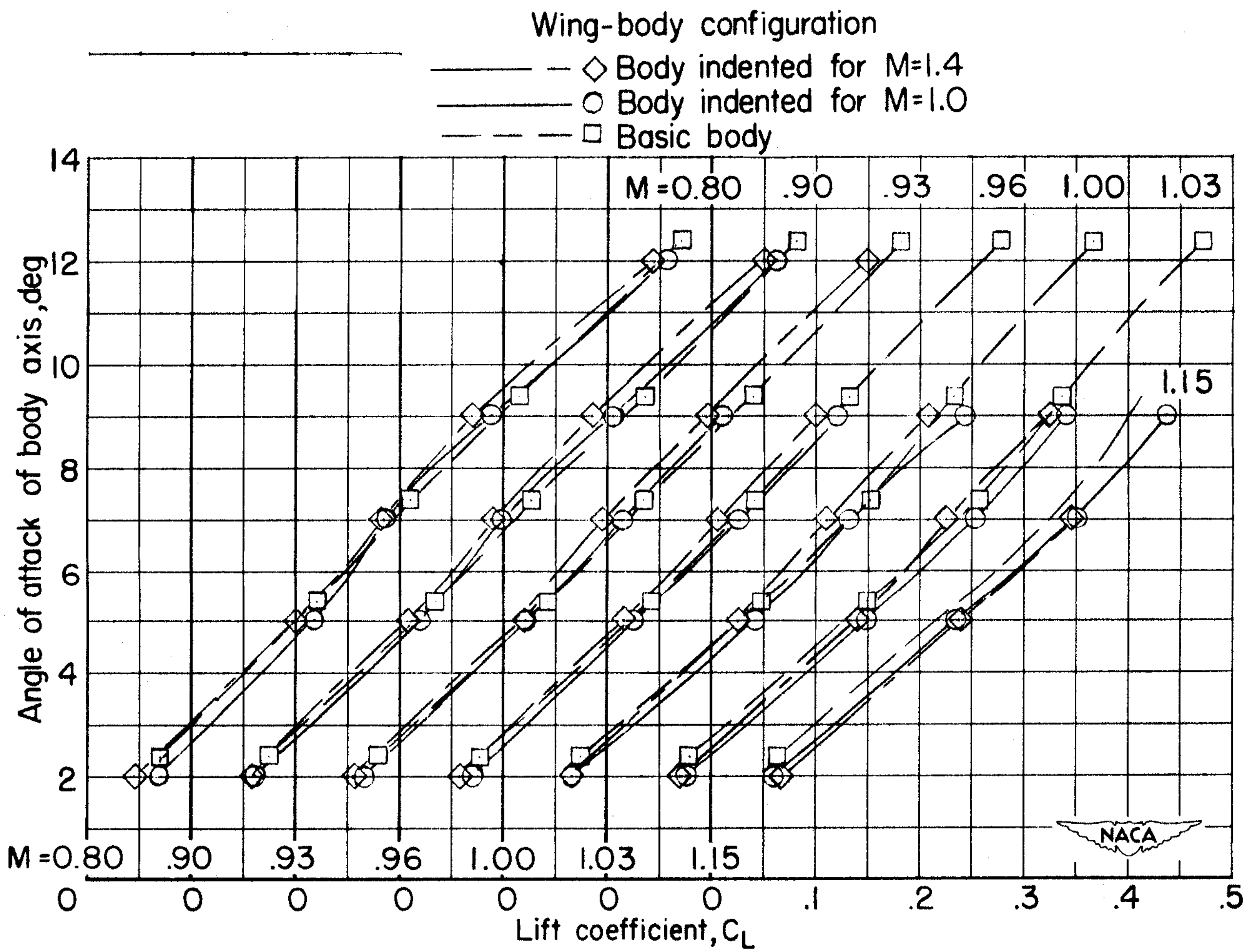
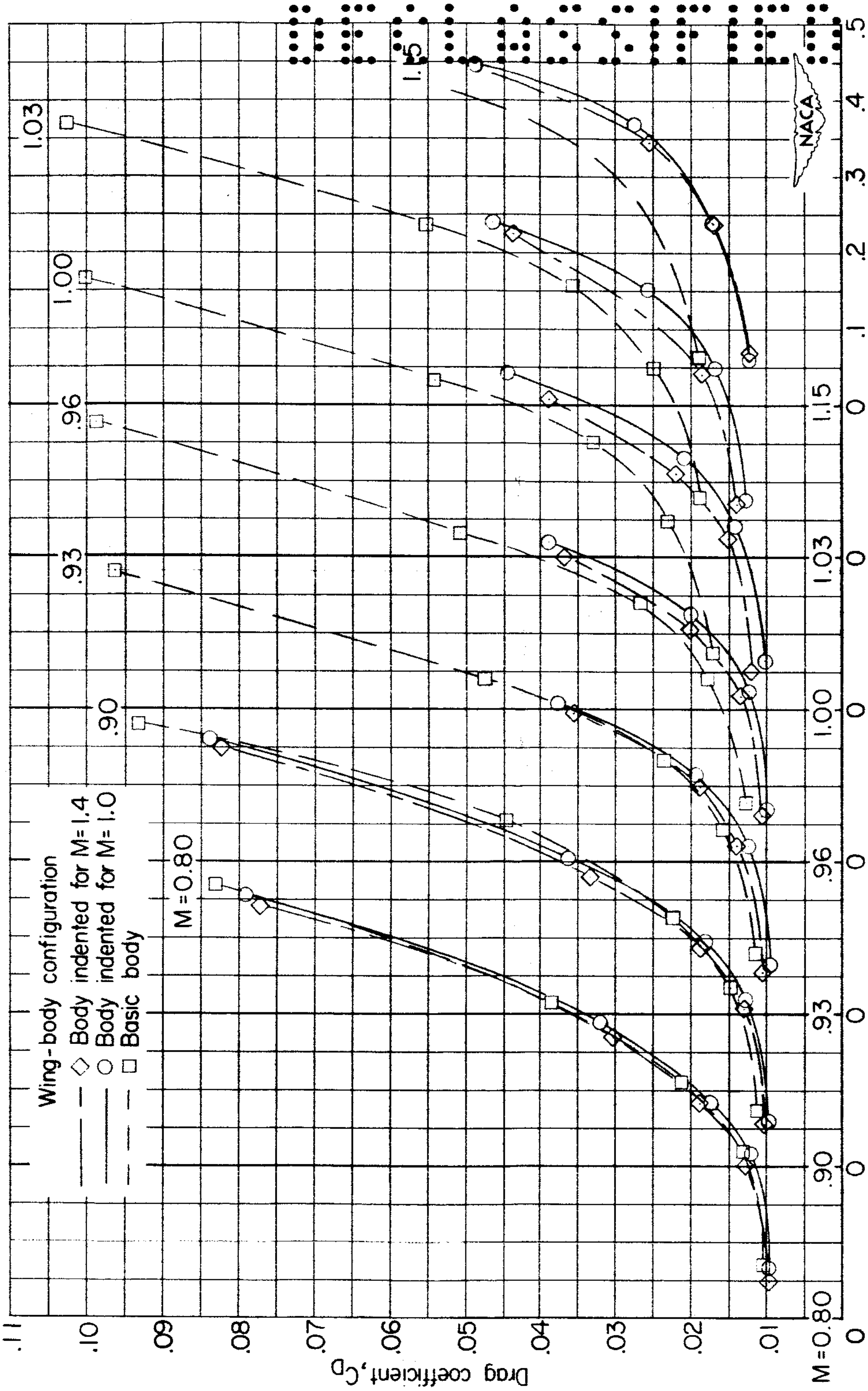


(a) Angle of attack.

Figure 8.- Angle of attack and drag coefficient versus lift coefficient for configurations tested.



(b) Drag coefficient.

Figure 8.- Concluded.

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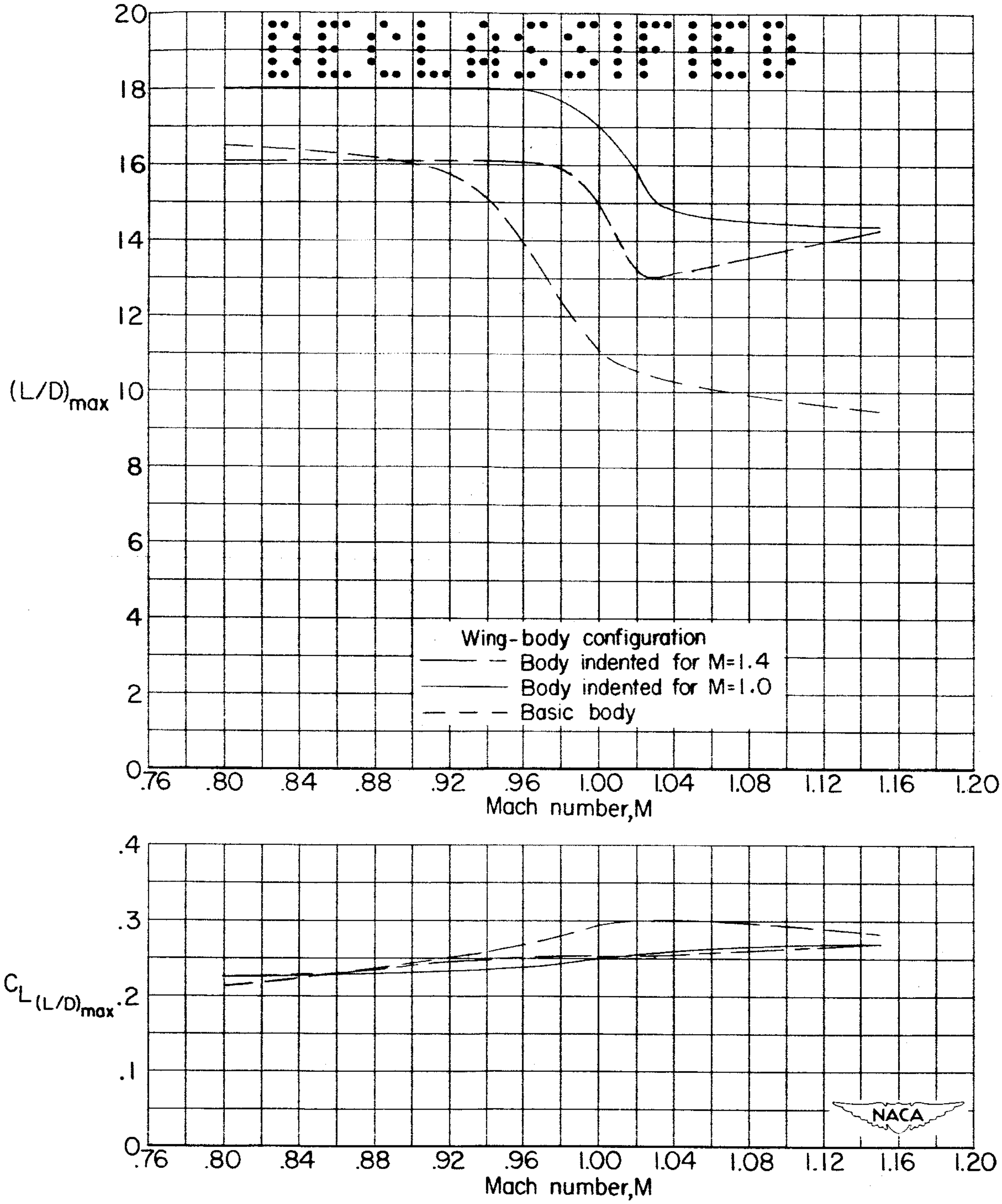

Figure 9.- Variation with Mach number of the maximum lift-to-drag ratios and the lift coefficients at which these values were obtained.

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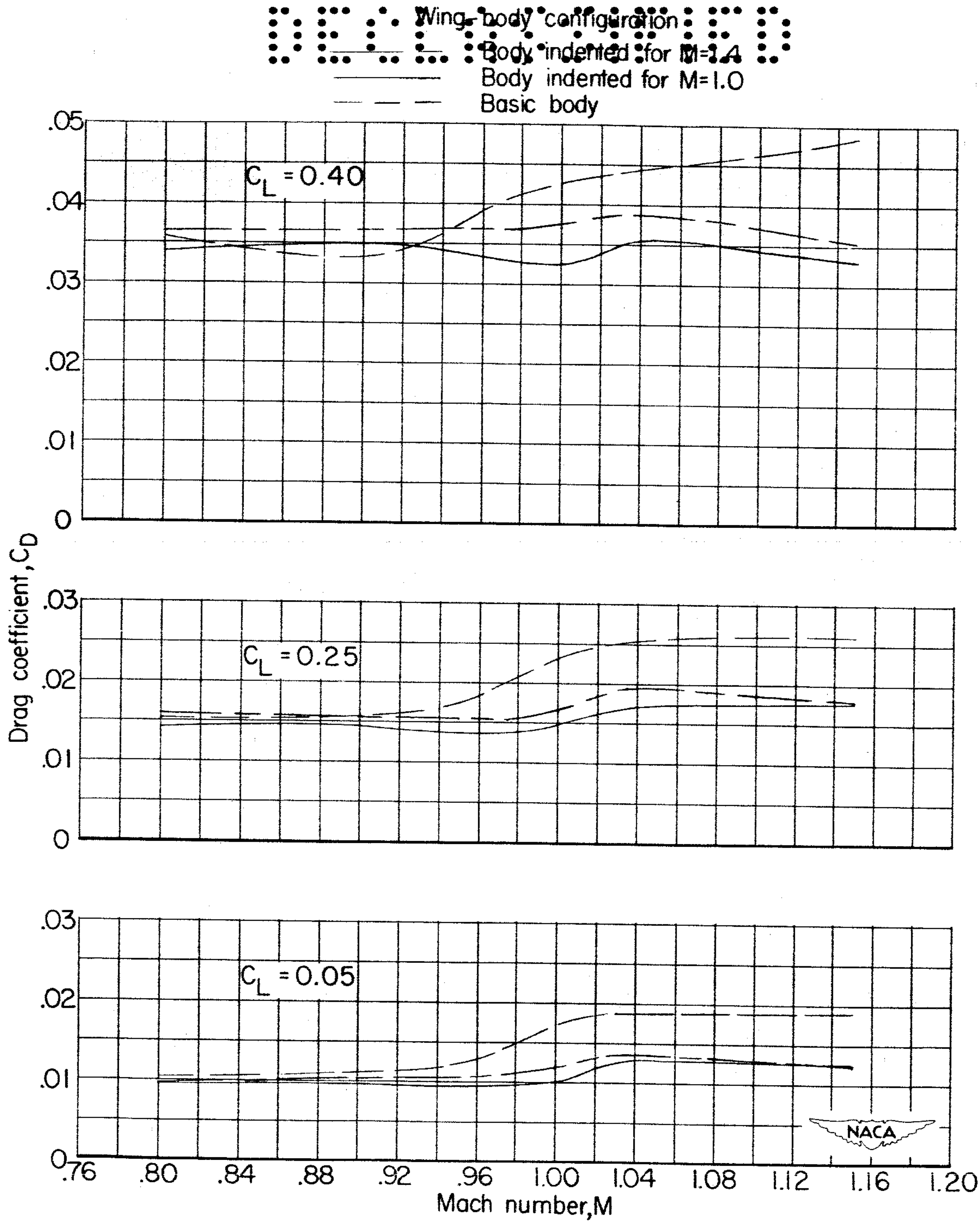

Figure 10.- Variations of drag coefficient at constant lift coefficient with Mach number.

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Wing-Fuselage Combinations - Airplanes	1.7.1.1.1

ABSTRACT

A concept for interrelating the wave drags of wing-body combinations at supersonic speeds with axial distributions of cross-sectional area is presented. A swept-wing—indented-body combination designed on the basis of this concept to have significantly improved maximum lift-to-drag ratios over a range of transonic and moderate supersonic speeds is described. Limited preliminary experimental results obtained for this configuration at Mach numbers to 1.15 are presented. A maximum lift-to-drag ratio of approximately 14 was obtained at a Mach number of 1.15.

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